The TTR in the NFAC 40- by 80-ft test section. In this photo, the TTR is oriented 45 degrees to the flow. Microphone stands for acoustics measurements are visible at the lower right.

Tiltrotor Test Rig Breaks New Ground

Record-Setting Proprotor Testing Completed in the NFAC 40- by 80-ft Wind Tunnel

By Wally Acree

NASA Ames Research Center has a long history of testing large-scale proprotors in the National Full-Scale Aerodynamics Complex (NFAC). The XV-15 was tested in the 1970s, both as an isolated rotor and as a full aircraft, and the JVX rotor (2/3-scale predecessor to the V-22) was tested in the 1980s through 1991. NASA needed a new, more capable facility for testing 21st-century proprotors. The Tiltrotor Test Rig (TTR) amply fulfills that need. In November, the testing achieved a maximum airspeed of 273 kt (506 kt) — the current NFAC facility limit. This is the highest airspeed ever achieved by a full-scale proprotor in any wind tunnel.

The TTR began as a collaborative effort between NASA and the US Army as part of the Joint Heavy Lift (JHL) program. Sizing studies were initiated in 2007, resulting in a NASA contract to Bell and Triumph Aerospace Systems Newport News (now Calspan Corporation) to design and manufacture the TTR and supporting equipment. The Army and Air Force contributed funding and support.

TTR Description

The TTR is designed to test advanced proprotors up to 26 ft (7.9 m) in diameter at speeds up to 300 kt (555 km/h). This combination of size and speed is unprecedented and is necessary for research into 21st-century tiltrotors and other advanced rotorcraft concepts. Even larger rotors can be tested at lower speeds, depending on the NFAC configuration. TTR provides critical data for validation of state-of-the-art design and analysis tools. The TTR is a horizontal axis rig that rotates on the test-section turntable to face the rotor into the wind at high speed (300 kt), fly edgewise at low speed (150 kt or 278 km/h), or at any angle in between. The turntable angle in the wind tunnel is equivalent to what the nacelle angle in flight would be. The TTR can also be rotated 180 degrees to face the rotor backwards.

The TTR has four electric motors capable of 5,000 hp (3,730 kW) total. The gearbox was designed for higher power — up to 6,000 hp (4,475 kW) — should that be needed for future rotors. The TTR has an all-electric control system, with dual-redundant actuators and control consoles.

For maximum accuracy, rotor forces are measured by a dedicated balance installed between the gearbox and the rotor. Rotor torque is measured by an instrumented drive shaft. All data were acquired by the NFAC data system, typically at 256 points per rotor revolution, but 2,048 points per revolution for acoustics data.

The TTR can accommodate a variety of rotors. A 26-ft (7.9 m) diameter research rotor (shown in the figure) was installed for the first test. The rotor was built specifically for NASA by Bell, derived from the right-hand rotor of the (now) Leonardo AW609 and equipped with additional instrumentation and other modifications for wind-tunnel testing. The unique wind-tunnel version of the rotor is designated Bell Model 699.

A critical requirement of the TTR is to measure rotor performance and loads more accurately than can be done in flight. To ensure accuracy, testing began even before the NFAC entry when the entire TTR was calibrated in a purpose-built calibration rig. The rotor was replaced by metric hardware (the black cross in the photo) so that flight loads could be simulated with hydraulic actuators. Deflections under load, although extremely small, were nevertheless important at high simulated thrust and torque. Photogrammetry techniques were used to measure any such deflections without physically contacting the measurement hardware.

Testing Summary

The first wind-tunnel entry was intended as a functional checkout, but proved so successful that the resulting research data extended far beyond any previous large-scale proprotor test. All testing was done in the 40- by 80-ft (12- by 24-m) test section of the NFAC. As mentioned above, the TTR reached 273 kt (505 km/h) in axial flow, which duplicated tiltrotor airplane mode, although the best-quality performance data were taken at 61–264 kt (113–489 km/h). Comprehensive high-speed data were taken at two different rotor tip speeds, 775 ft/s and 651 ft/s (236 m/s and 198 m/s), equivalent to helicopter and airplane mode operation. The actual aircraft cannot be flown at those rotor speeds over the full range of airspeeds tested in the NFAC. Even as a checkout test, the TTR entry demonstrated the utility of wind tunnel testing for providing full-scale data under conditions not safely achievable in flight. Maximum airspeed was limited by load limits on the NFAC, not the rotor or TTR, so even higher airspeeds should be capable with upgrades to the NFAC, including adding fairings to the support struts.

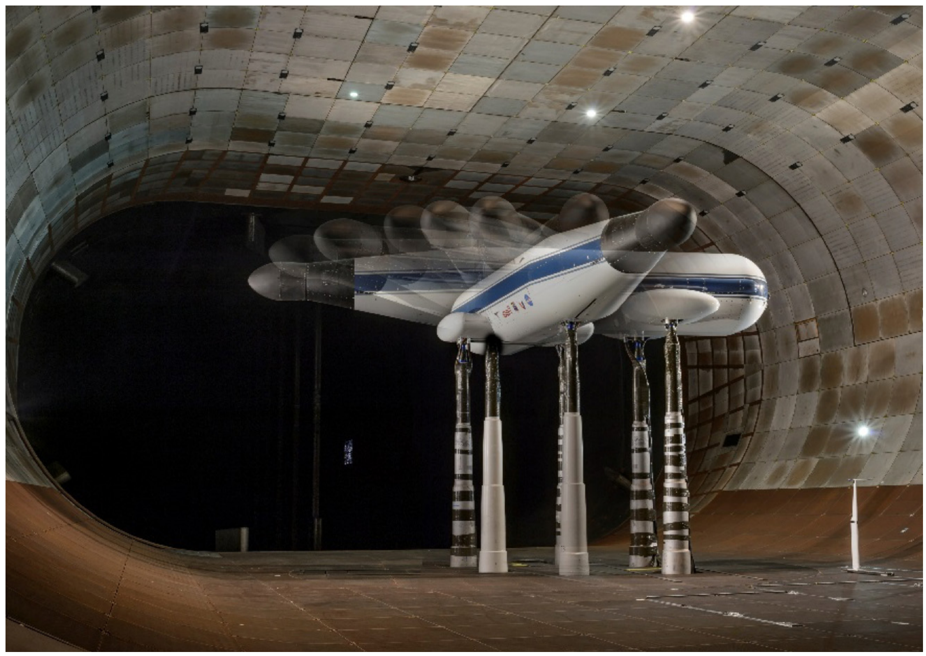
The rotor was also tested in near-hover conditions with the NFAC fan drives turned off. For the TTR entry, the NFAC was configured as a closed-circuit tunnel. In that configuration, the downwash from the rotor in hover continued around the circuit, thereby simulating vertical climb conditions at the rotor. The TTR was tested with several different settings of wind tunnel vents, louvers, and guide vanes, and with the rotor oriented both upstream and downstream, to evaluate the effects of the wind tunnel on rotor performance at low vertical climb speeds.

In addition to vertical climb and high-speed airplane mode, the rotor was tested at 29 combinations of airspeed and turntable angle, which simulated the full range of the aircraft conversion envelope. Yet more data were taken at low speed and very fine increments of turntable angle to provide detailed acoustics data.

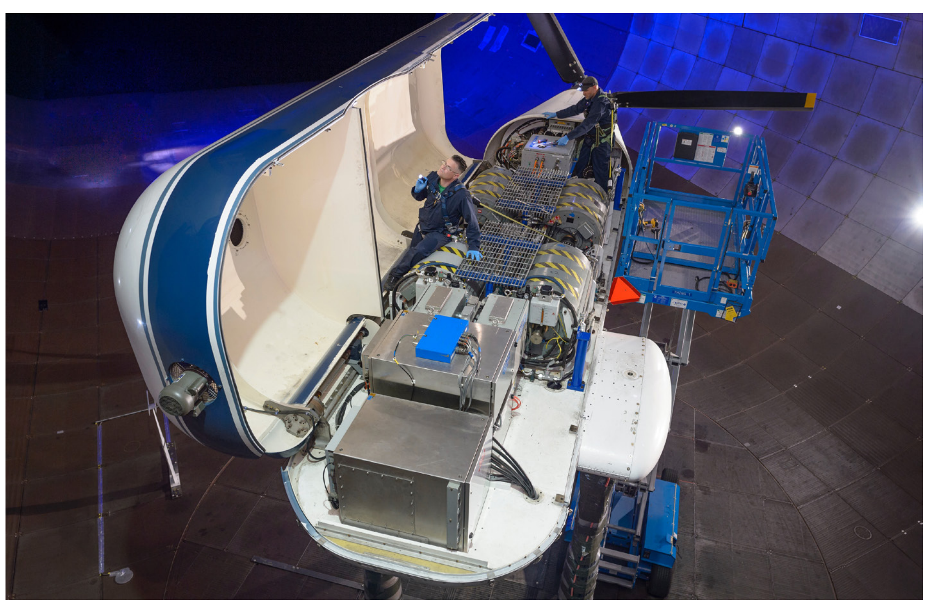
The rotor has a large spinner that generates aerodynamic loads quite different from a helicopter rotor hub. The resulting aerodynamic tare loads were measured by testing the TTR with the rotor removed, as shown in the photograph. The multiple-exposure photo also shows the rotation of the TTR on the wind tunnel turntable. Testing without a rotor is much easier and faster than with a rotor, so a small amount of testing yielded a lot of spinner tare data. Additional data included motor tests, thermal tests, modal vibration tests and other checkout activities.

Summary

In total, the first wind-tunnel test of the TTR included more than 1,550 rotor data points, over 550 spinner tare data points and over 1,200 additional diagnostics data



The TTR configured for spinner tare measurements, without the rotor. The multiple-exposure photo shows the full range of conversion mode angles.



The NFAC crew performing a routine inspection of the TTR. The large boxes are electronics cabinets, and the four striped cylinders are the drive motors.

points (such as temperature checks). The data collected include traditional rotor performance parameters, control inputs and loads, and blade loads at multiple spanwise stations. Additional data included motor tests, thermal tests, modal vibration tests, and other checkout activities. The database is undergoing extensive validation to ensure it meets NASA standards, after which all data will be released to the public.

Taken together, these accomplishments thoroughly demonstrated the capability of the TTR up to the limits of the NFAC operating envelope while providing a comprehensive database of benchmark rotor data. The test also identified upgrades to improve productivity and extend the test envelope to support future rotor testing. The TTR/699 test generated an unprecedented collection of full-scale proprotor performance, loads and acoustics data, constituting a major advancement over previous testing capability.

About the Author

C. W. Acree, Jr. (Wally) joined NASA Ames Research Center in 1978 and has participated in a variety of flight and wind-tunnel tests. He was the program director for the Tiltrotor Test Rig throughout its development and testing. Mr. Acree recently retired from NASA but remains an active researcher as an Ames Associate.

Further Reading

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- Solis, E., and Meyn, L., "Photogrammetric Deflection Measurements for the Tiltrotor Test Rig (TTR) Multi-Component Rotor Balance Calibration," Vertical Flight Society Technical Meeting on Aeromechanics Design for Vertical Lift Proceedings, San Francisco, California, January 2016.

To learn more about the TTR and other NASA rotorcraft research, visit: rotorcraft.arc.nasa.gov